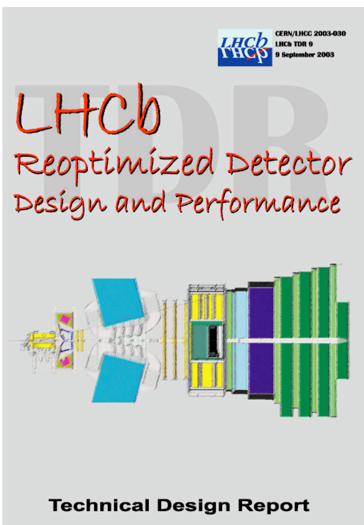
Performance Studies for the LHCb Experiment



Marcel Merk

NIKHEF

Representing the LHCb collaboration

19 th International Workshop
on Weak Interactions and Neutrinos
Oct 6-11, Geneva, Wisconsin, USA

B Physics in 2007

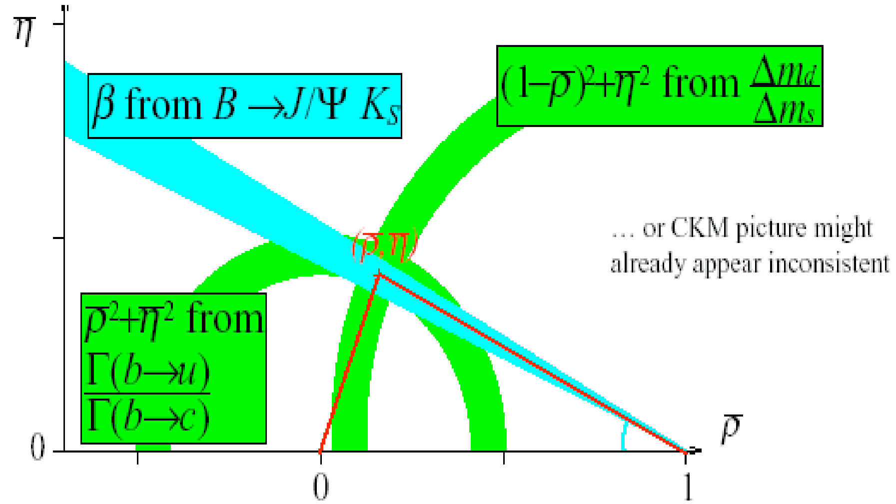
- Direct Measurement of angles:
  - □(sin(2□)) ≈ 0.03 from J/□ Ks in B factories
  - Other angles not precisely known

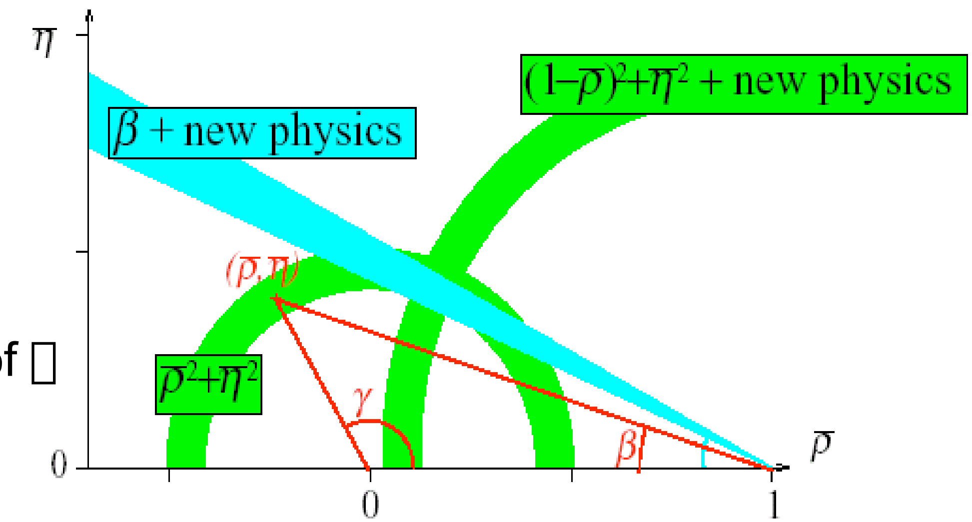
- Knowledge of the sides of unitary triangle:

  (Dominated by theoretical uncertainties)
  - □($|V_{cb}|$) ≈ few % error
  - □($|V_{ub}|$) ≈ 5-10 % error
  - □($|V_{td}|/|V_{ts}|$) ≈ 5-10% error

    (assuming □m_s < 40 ps^{-1})

- In case new physics is present in mixing, independent measurement of □ can reveal it…

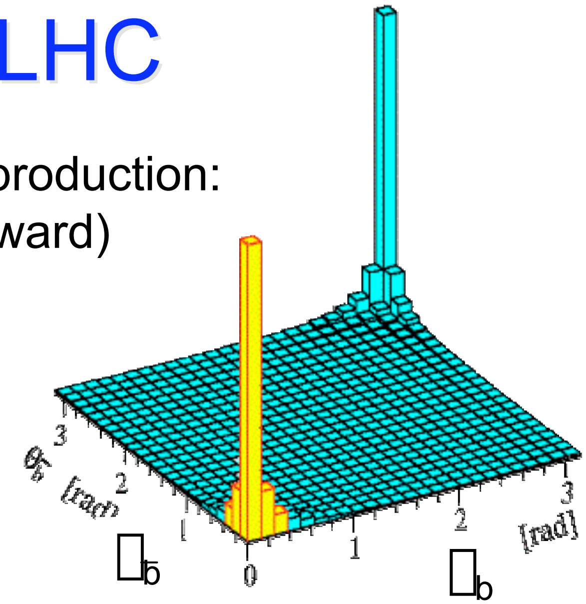




B Physics @ LHC

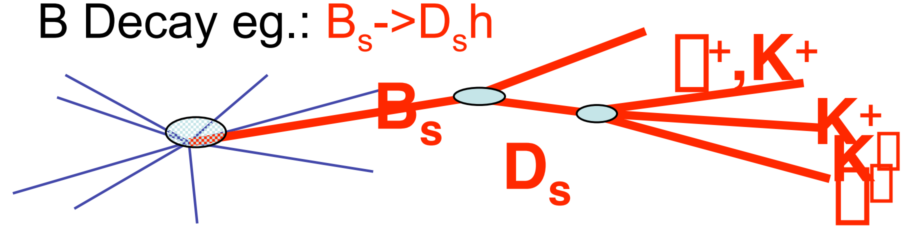
√s	14 TeV
L (cm^{-2} s^{-2})	$2x10^{32}$ cm^{-2} s^{-1}
σ_{bb}	500 μb
σ_{inel} / σ_{bb}	160

$b\bar{b}$ production:
(forward)



- ☺ Large bottom production cross section:
  10^{12} bb/year at $2x10^{32}$ $cm^{-2}s^{-1}$
- 😐 Triggering is an issue
- ☺ All b hadrons are produced:
  B_u (40%), B_d(40%), B_s(10%), B_c and b-baryons (10%)
- ☺ Many tracks available for primary vertex
- ☹ Many particles not associated to b hadrons
- ☹ b hadrons are not coherent: mixing dilutes tagging

B Decay eg.: B_s->D_sh

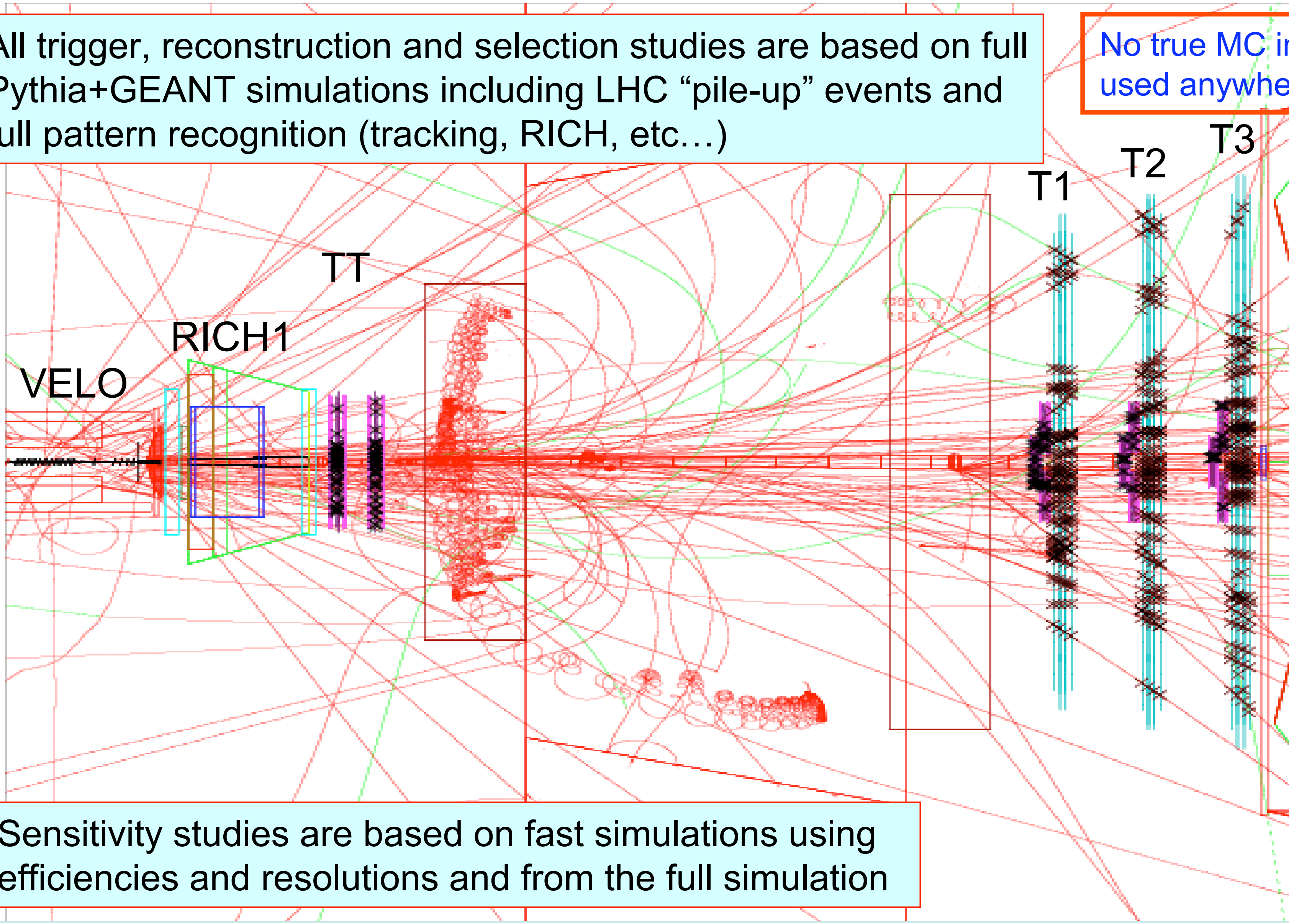


<u>LHCb: Forward Spectrometer with:</u>
- Efficient trigger and selection of many B decay final states
- Good tracking and Particle ID performance
- Excellent momentum and vertex resolution
- Adequate flavour tagging

Simulation and Reconstruction

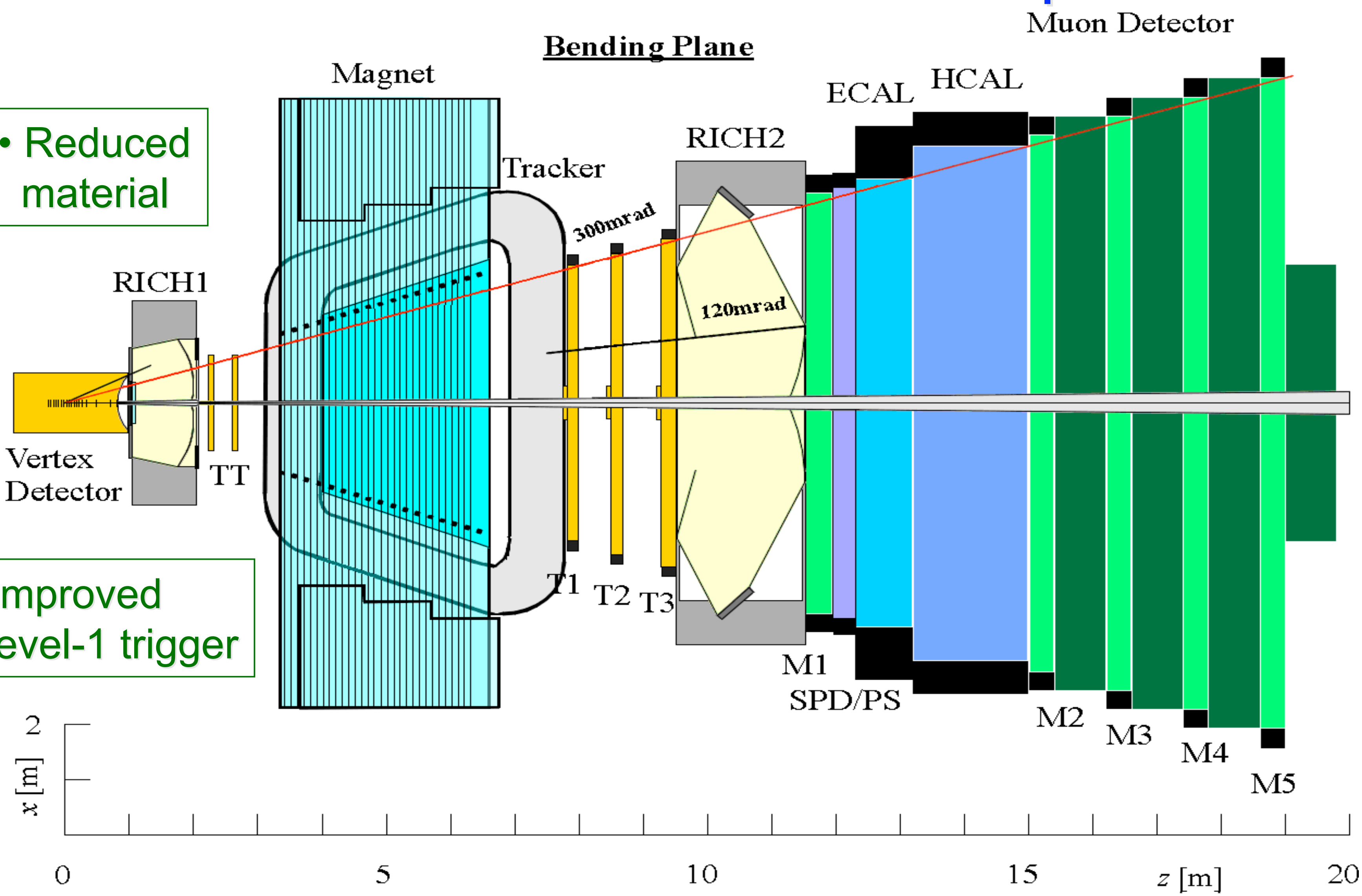
All trigger, reconstruction and selection studies are based on full Pythia+GEANT simulations including LHC “pile-up” events and full pattern recognition (tracking, RICH, etc…)

No true MC info used anywhere !



Sensitivity studies are based on fast simulations using efficiencies and resolutions and from the full simulation

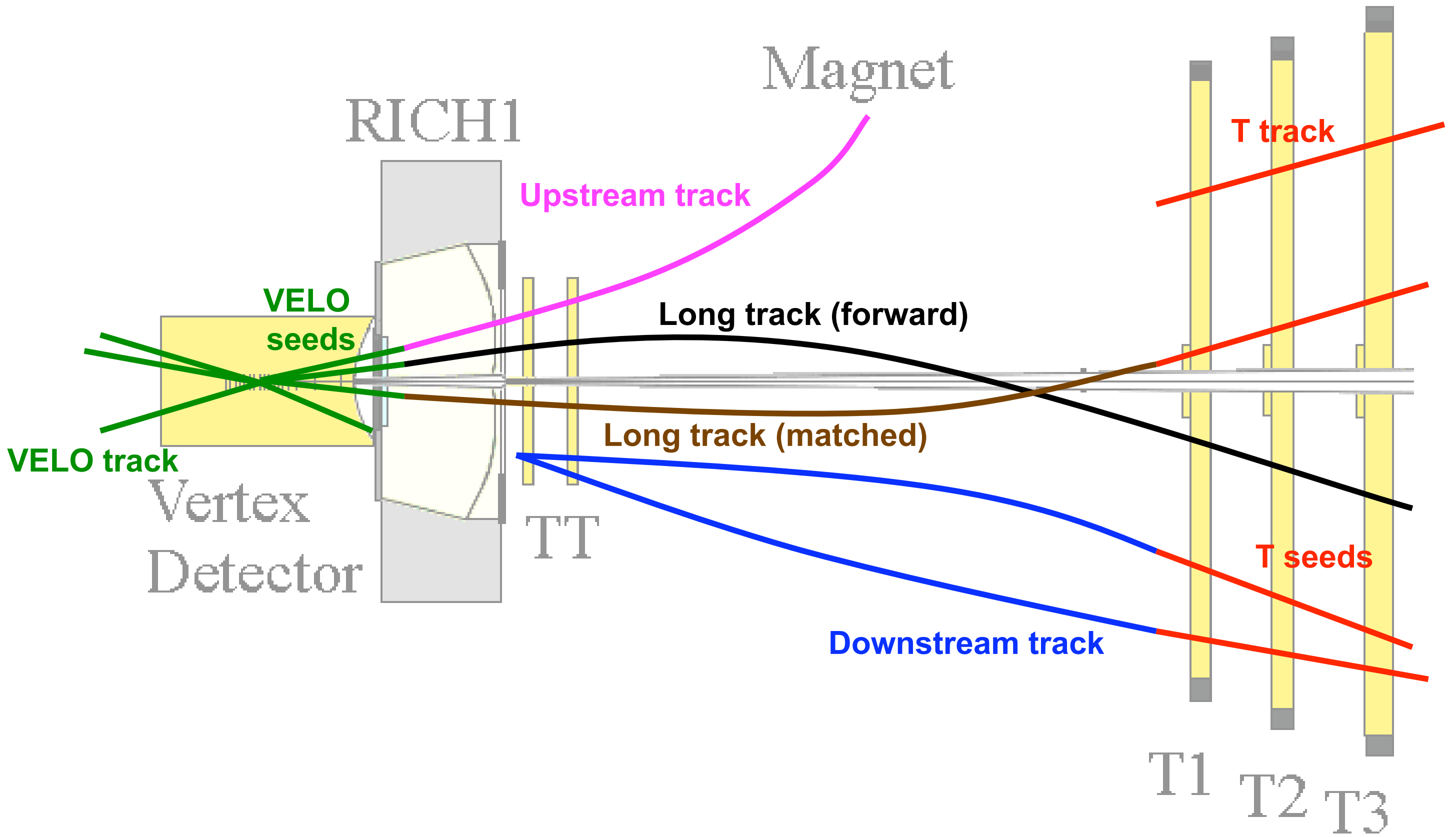
Evolution since Technical Proposal



- Reduced material

- Improved level-1 trigger

Track finding strategy



Long tracks	→	highest quality for physics (good IP & p resolution)
Downstream tracks	→	needed for efficient K_S finding (good p resolution)
Upstream tracks	→	lower p, worse p resolution, but useful for RICH1 pattern recognition
T tracks	→	useful for RICH2 pattern recognition
VELO tracks	→	useful for primary vertex reconstruction (good IP resolution)

Result of track finding

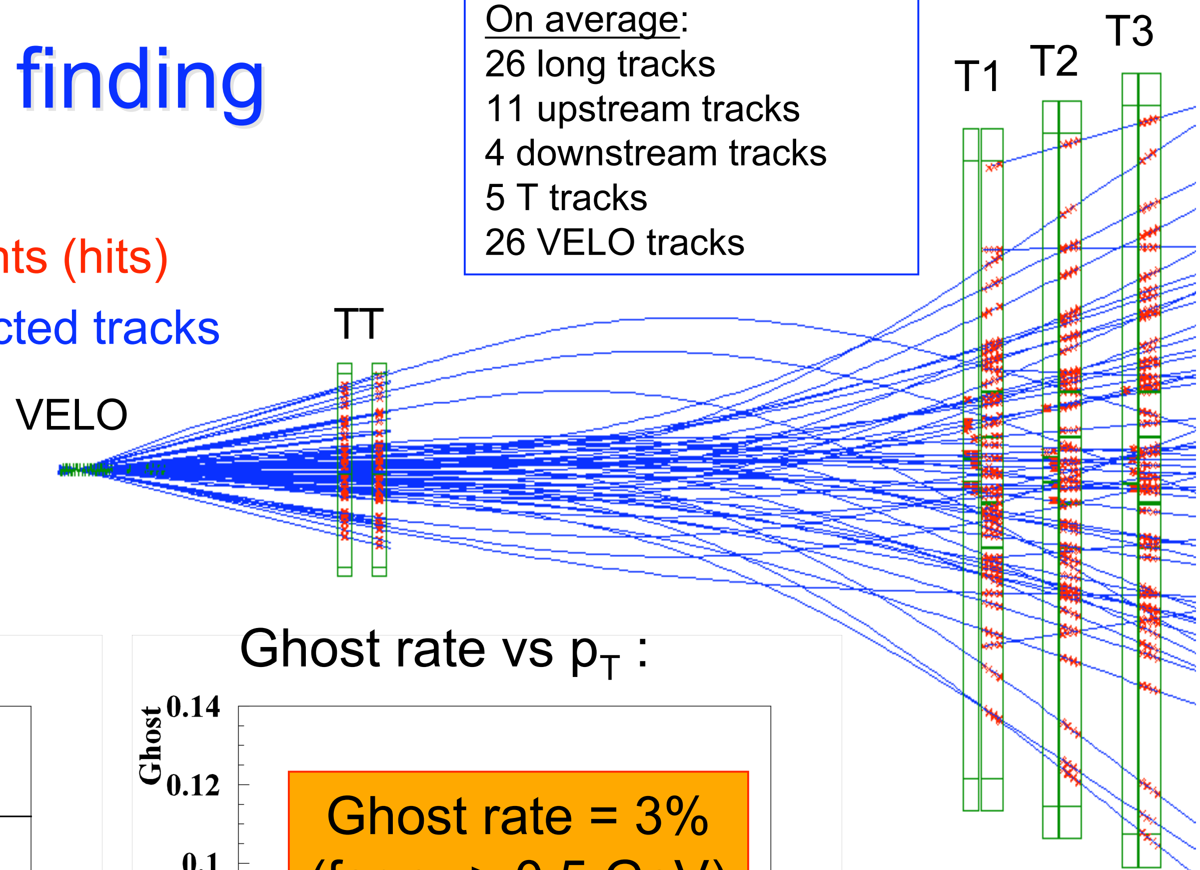
Typical event display:

Red = measurements (hits)

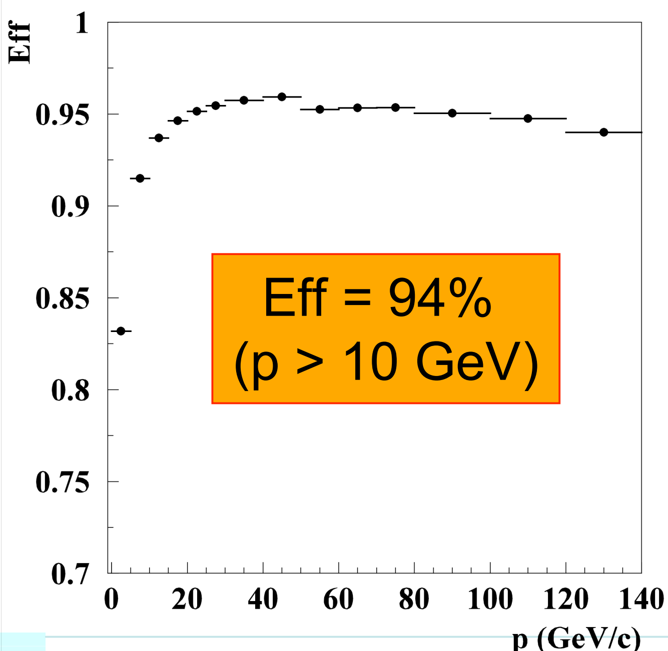
Blue = all reconstructed tracks

<u>On average</u>:
26 long tracks
11 upstream tracks
4 downstream tracks
5 T tracks
26 VELO tracks

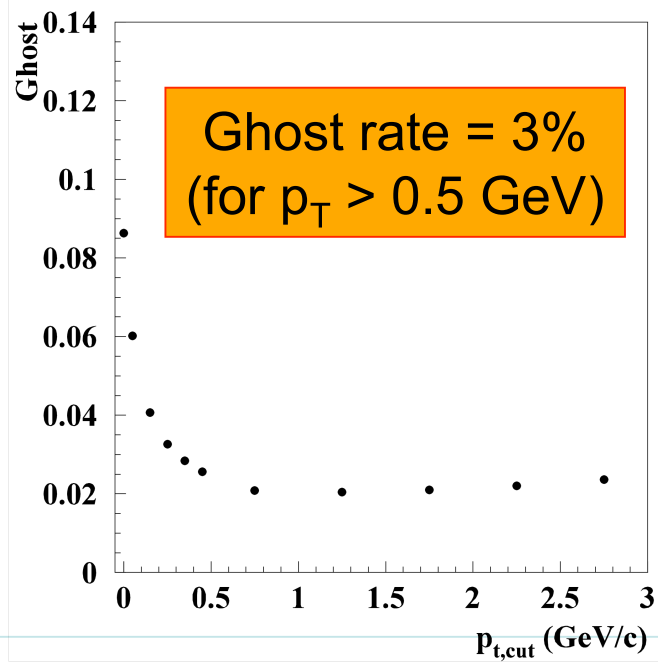
20–50 hits assigned to a long track:
98.7% correctly assigned



Efficiency vs p :



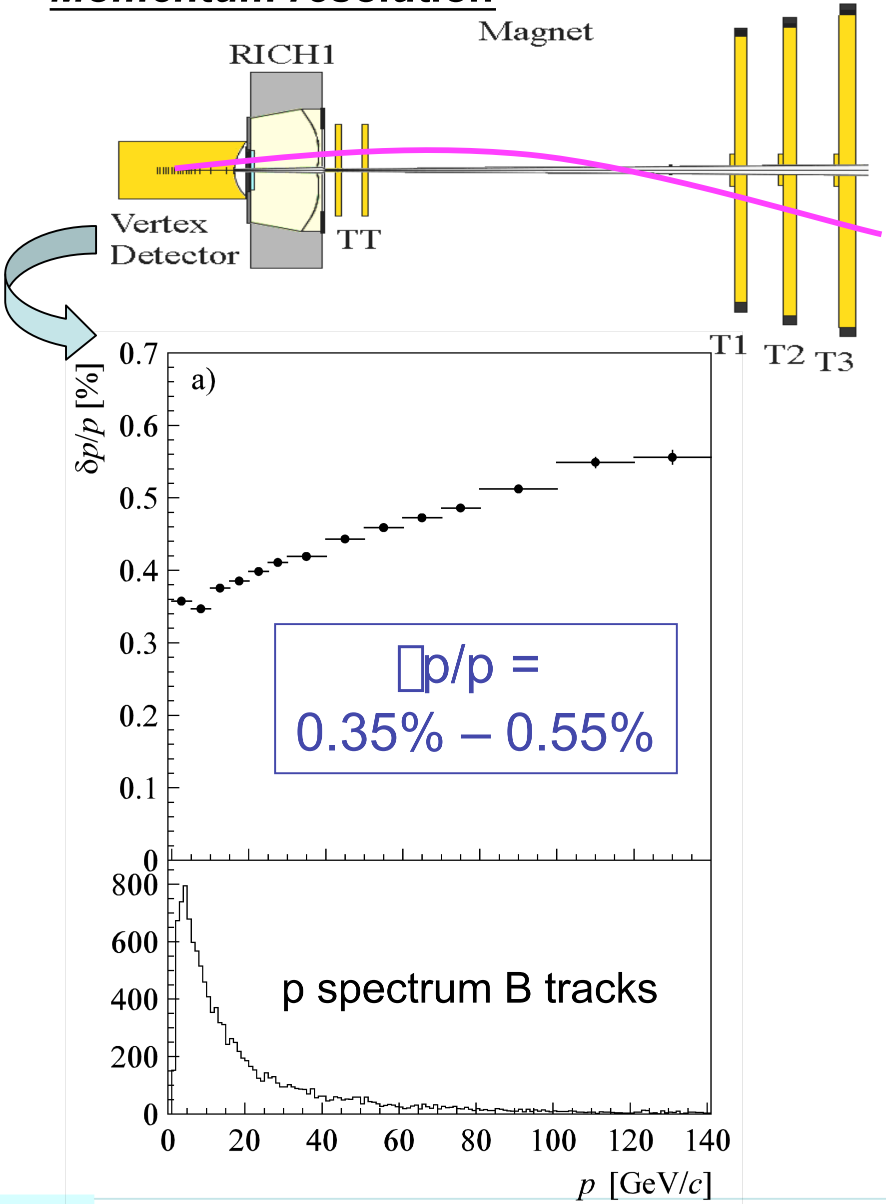
Ghost rate vs p_T :



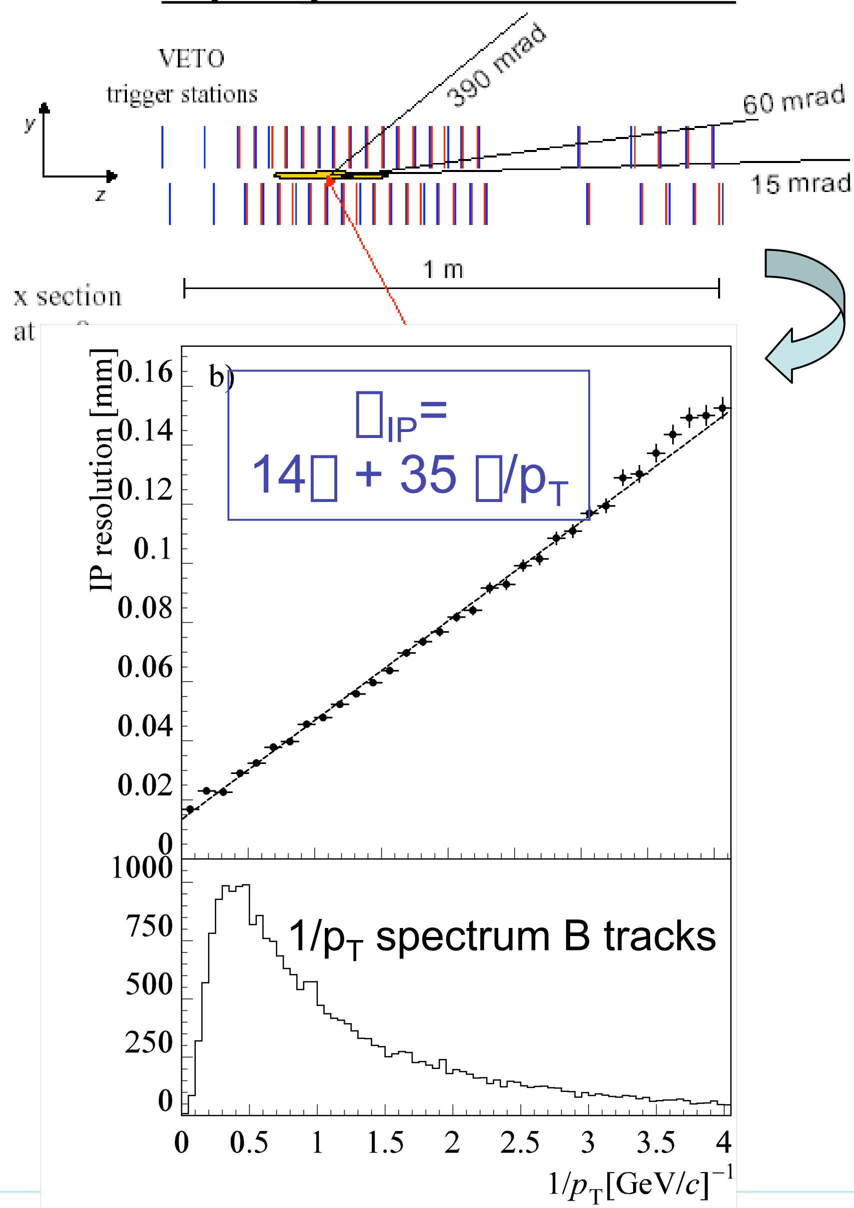
Ghosts:
Negligible effect on
b decay reconstruction

Experimental Resolution

Momentum resolution

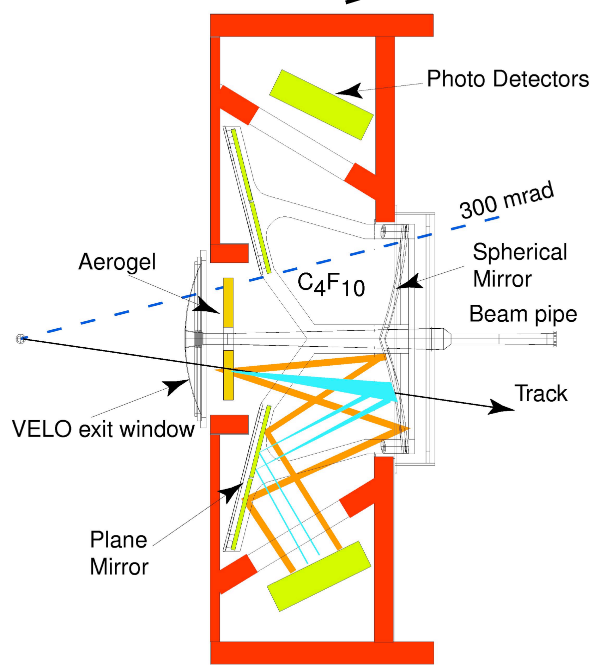


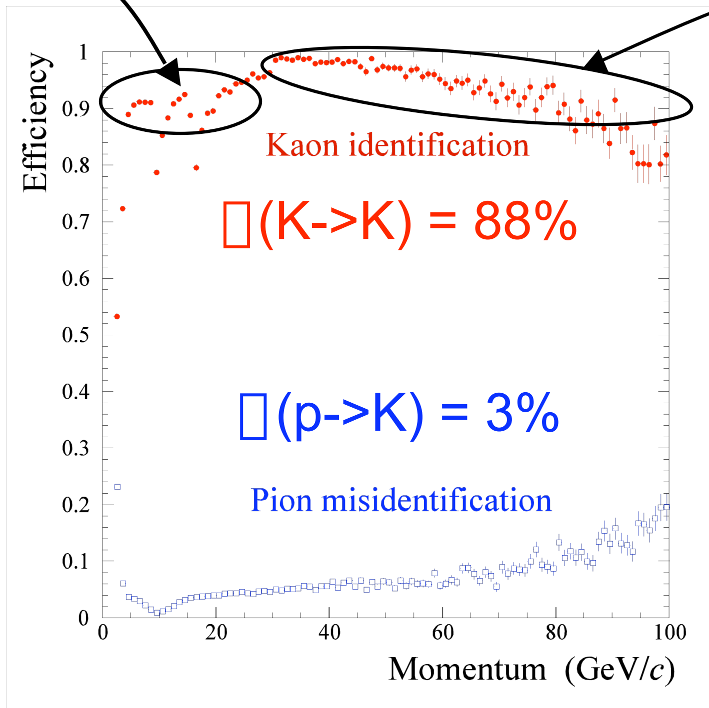
Impact parameter resolution



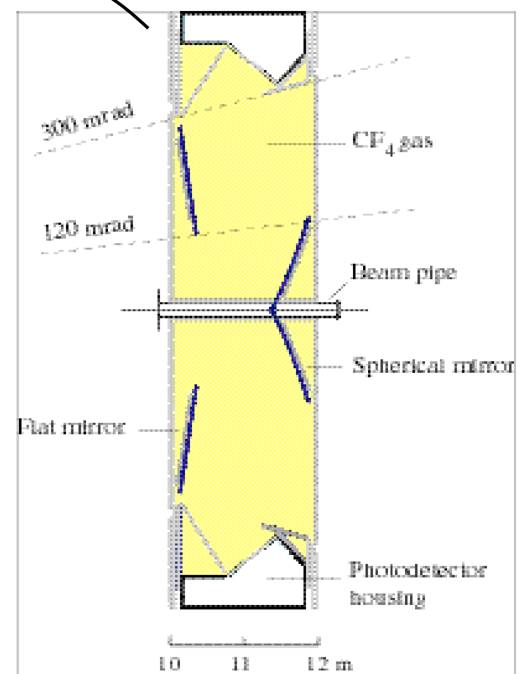
Particle ID

RICH 1



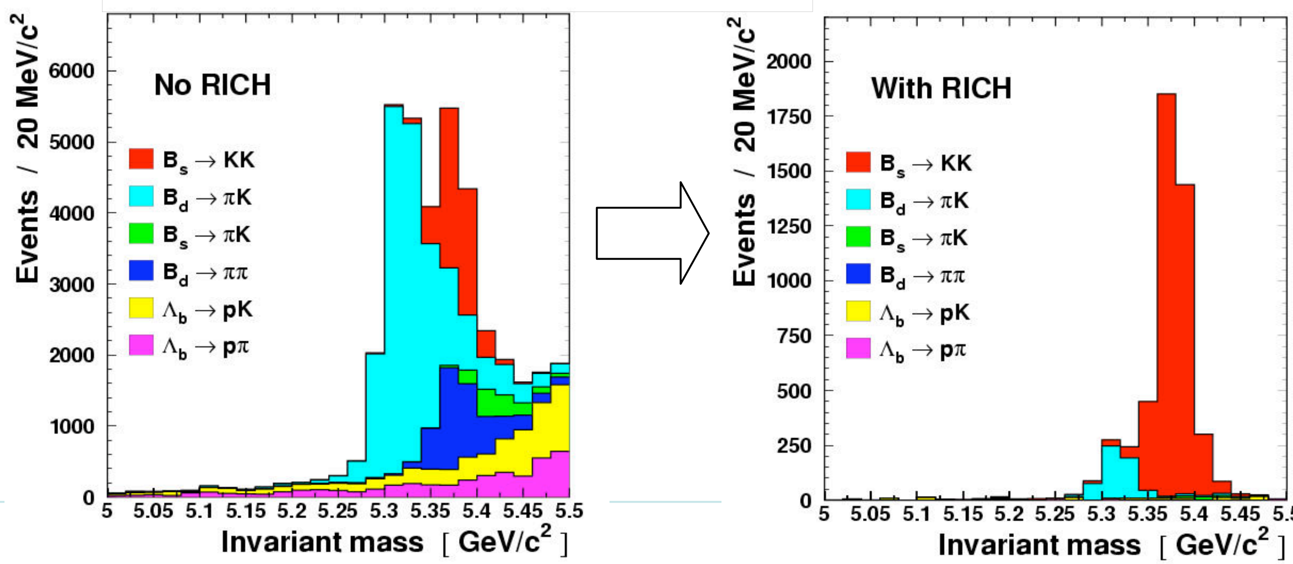


RICH 2



Example:

B->hh decays:



Trigger

40 MHz

Level-0:
p_T of
μ, e, h, γ

← Calorimeter / Muon system / Pile-up system

1 MHz

Level-1:
Impact parameter
Rough p_T ~ 20%

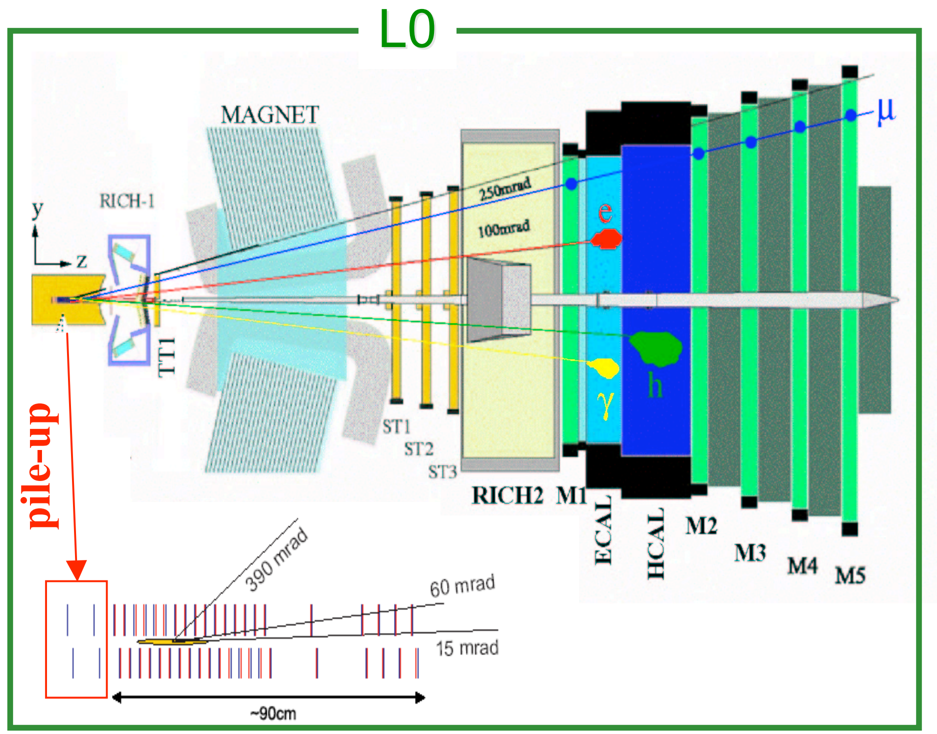
← Vertex Locator / Trigger Tracker / Level 0 objects

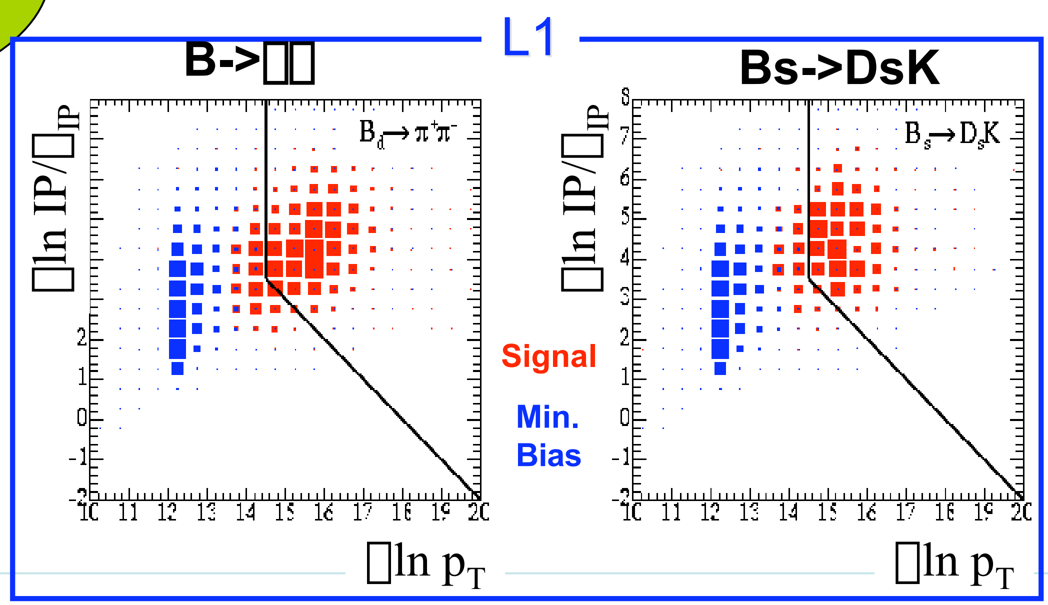
40 kHz

HLT:
Final state reconstruction

← Full detector information

200 Hz output



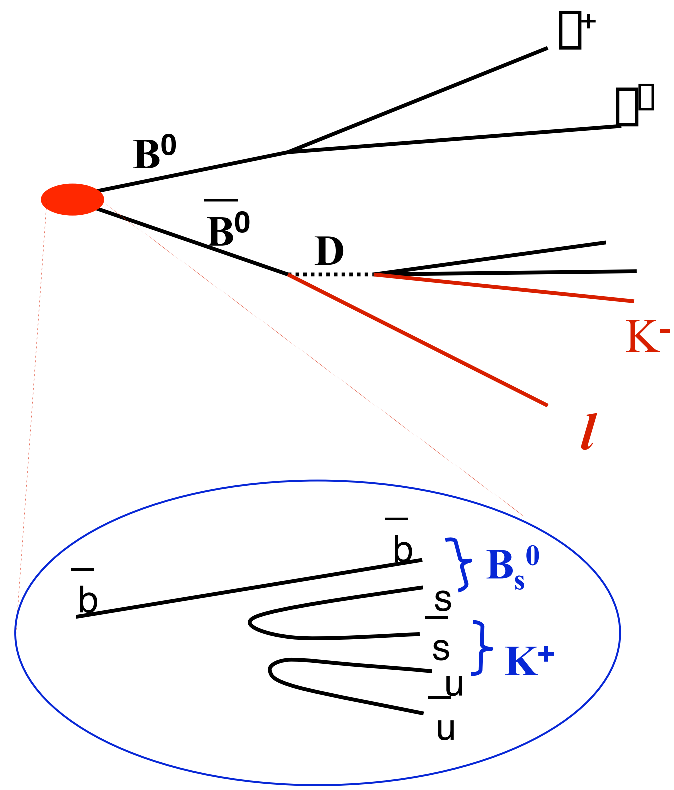


Flavour tag

Knowledge of flavour at birth is essential for the majority of ~~CP~~ measurements

tagging strategy:

- opposite side lepton tag (b _ *l*)
- opposite side kaon tag (b _ c _ s) (RICH, hadron trigger)
- same side kaon tag (for B_s)
- opposite B vertex charge tagging



sources for wrong tags:

B_d-$\bar{B}_d$ mixing (opposite side)

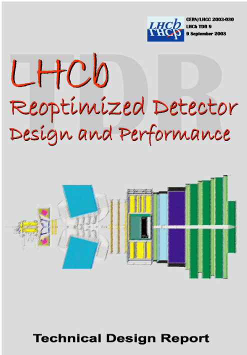
b _ c _ *l* (lepton tag)

conversions…

effective efficiency:

$\varepsilon_{eff} = \varepsilon_{tag} (1-2w_{tag})^2$

Combining tags	ε_{tag} [%]	Wtag [%]	ε_{eff} [%]
B_d □ □□	42	35	4
B_s □ K K	50	33	6



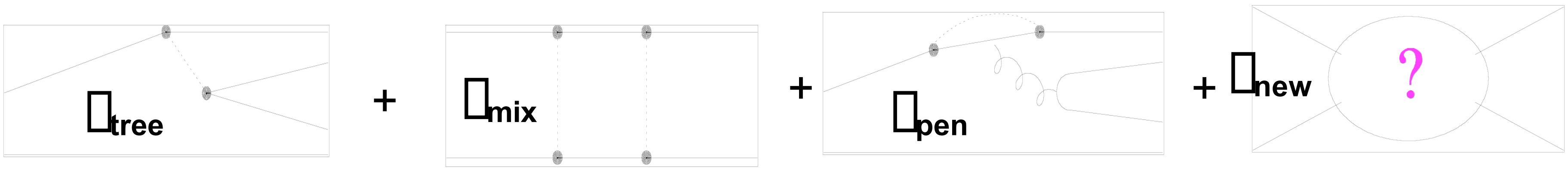
Efficiencies, event yields and B_{bb}/S ratios

	Det. eff. (%)	Rec. eff. (%)	Sel. eff. (%)	Trig. eff. (%)	**Tot. eff. (%)**	Vis. BR (10^{-6})	**Annual signal yield**	**B/S from bb bkg.**
$B^0 \to \pi^+\pi^-$	12.2	91.6	18.3	33.6	**0.69**	4.8	**26k**	**< 0.7**
$B_s \to K^+K^-$	12.0	92.5	28.6	36.7	**0.99**	18.5	**37k**	**0.3**
$B_s \to D_s^-\pi^+$	5.4	80.6	25.0	31.1	**0.34**	120.	**80k**	**0.3**
$B_s \to D_s^{\mp}K^{\pm}$	5.4	82.0	20.6	29.5	**0.27**	10.	**5.4k**	**< 1.0**
$B^0 \to \bar{D}^0(K\pi)K^{*0}$	5.3	81.8	22.9	35.4	**0.35**	1.2	**3.4k**	**< 0.5**
$B^0 \to J/\psi(\mu\mu)K^0_S$	6.5	66.5	53.5	60.5	**1.39**	20.	**216k**	**0.8**
$B^0 \to J/\psi(ee)K^0_S$	5.8	60.8	17.7	26.5	**0.16**	20.	**26k**	**1.0**
$B_s \to J/\psi(\mu\mu)\phi$	7.6	82.5	41.6	64.0	**1.67**	31.	**100k**	**< 0.3**
$B_s \to J/\psi(ee)\phi$	6.7	76.5	22.0	28.0	**0.32**	31.	**20k**	**0.7**
$B^0 \to \rho\pi$	6.0	65.5	2.0	36.0	**0.03**	20.	**4.4k**	**< 7.1**
$B^0 \to K^{*0}\gamma$	9.5	86.8	5.0	37.8	**0.16**	29.	**35k**	**< 0.7**
$B_s \to \phi\phi$	9.7	86.3	7.6	34.3	**0.22**	21.	**9.3k**	**< 2.4**

Nominal year = 10^{12} bb pairs produced (10^7 s at $L=2\times10^{32}$ cm^{-2}s^{-1} with σ_{bb}=500 μb)
Yields include factor 2 from CP-conjugated decays
Branching ratios from PDG or SM predictions

CP Sensitivity studies

CP asymmetries due to interference of Tree, Mixing, Penguin, New Physics amplitudes:



Mixing phases:

- Time dependent asymmetry in B_d->J/□ K_s decays
  - Sensitive to $□_d$
- Time dependent asymmetry in B_s->J/□ □decays
  - Sensitive to $□_s$

Measurements of Angle □:

1. Time dependent asymmetries in Bs->DsK decays. Interference between b->u and b->c tree diagrams due to Bs mixing
   - Sensitive to □+ $□_s$ (Aleksan et al)
2. Time dependent asymmetries in B->□□ and Bs->KK decays. Interference between b->u tree and b->d(s) penguin diagrams
   - Sensitive to □, $□_d$, $□_s$ (Fleischer)
3. Time Integrated asymmetries in B-> DK* decays. Interference between b->u and b->c tree diagrams due to D-D mixing
   - Sensitive to □ (Gronau-Wyler-Dunietz)

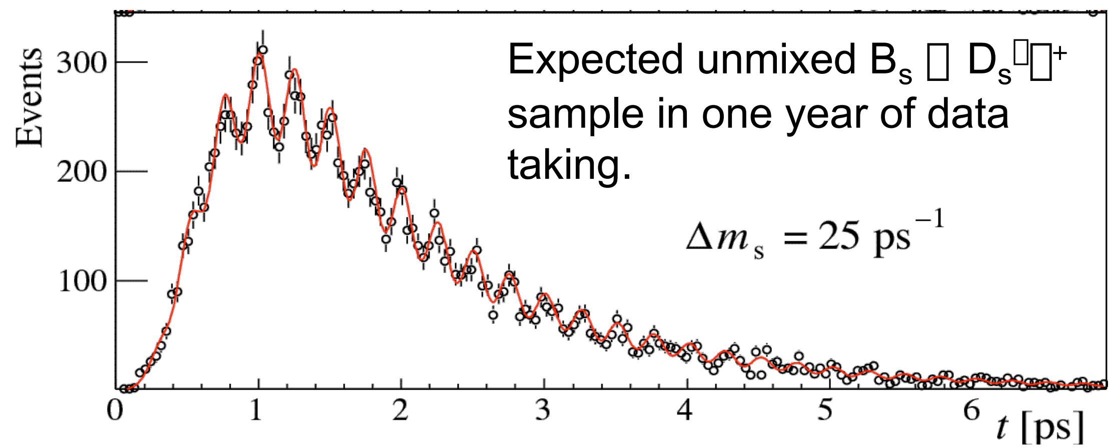
LHCb

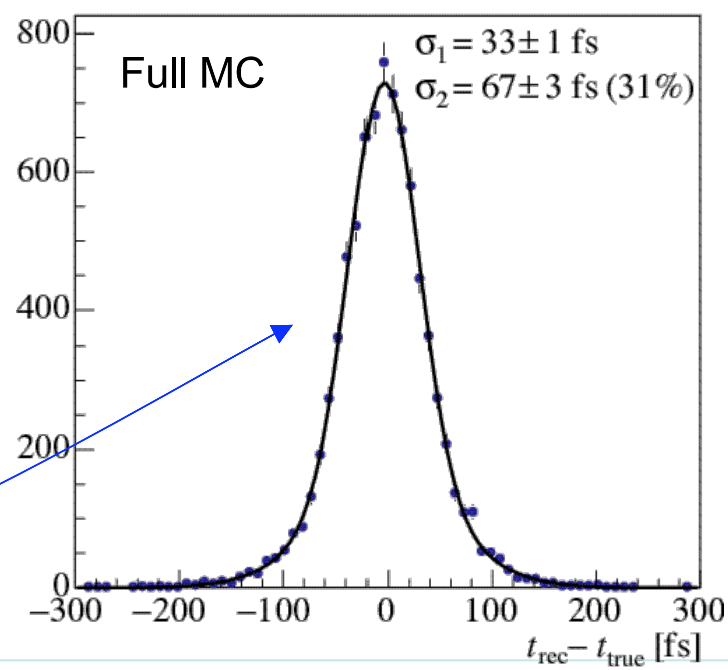
B_s oscillation frequency: Δm_s

- Needed for the observation of CP asymmetries with B_s decays
- Use $B_s \to D_s^- \pi^+$
- If $\Delta m_s = 20\ \text{ps}^{-1}$

$\sigma(\Delta m_s) = 0.011\ \text{ps}^{-1}$

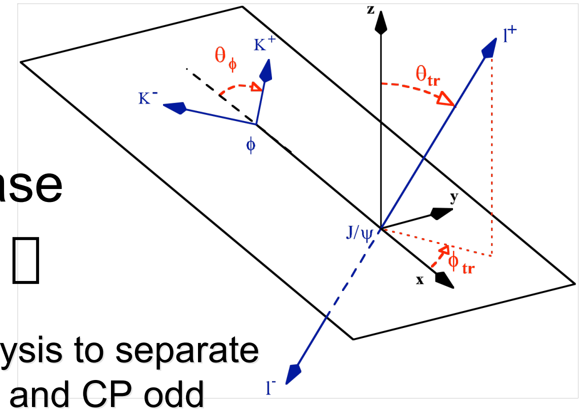
- Can observe >5σ oscillation signal if **$\Delta m_s < 68\ \text{ps}^{-1}$** well beyond SM prediction





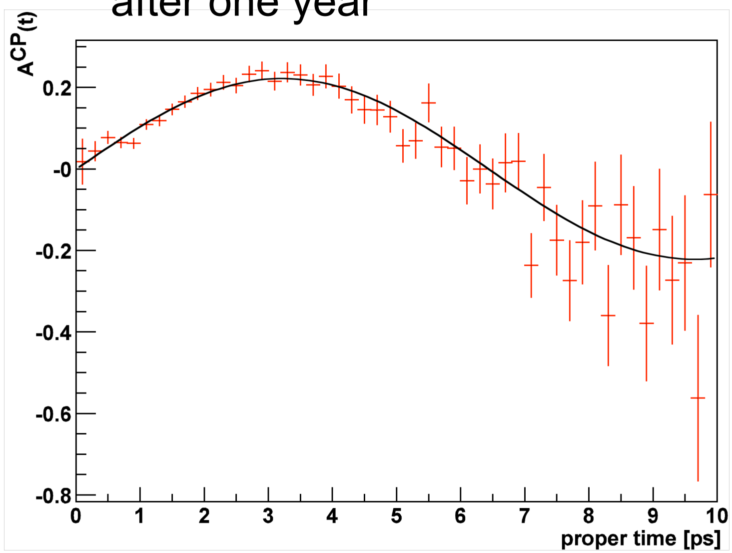
Proper-time resolution plays a crucial role

Mixing Phases



- Bd mixing phase using B->J/ψ K_s

Background-subtracted
$B^0 \to J/\psi(\mu\mu)K_S$ CP asymmetry
after one year

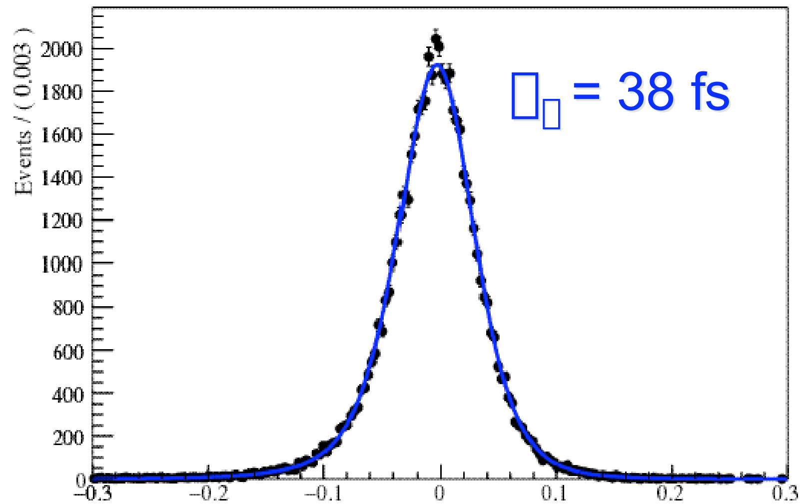


$\sigma(\sin(\phi_d)) = 0.022$

- Bs mixing phase using B_s->J/ψ φ

Angular analysis to separate
CP even and CP odd

Time resolution is important:



Proper time resolution (ps)

If Δm_s= 20 ps^{-1}: $\sigma(\Delta\Gamma_s/\Gamma_s) = 0.018$

<u>NB</u>: In the SM,
$\phi_s = -2\chi \sim -0.04$

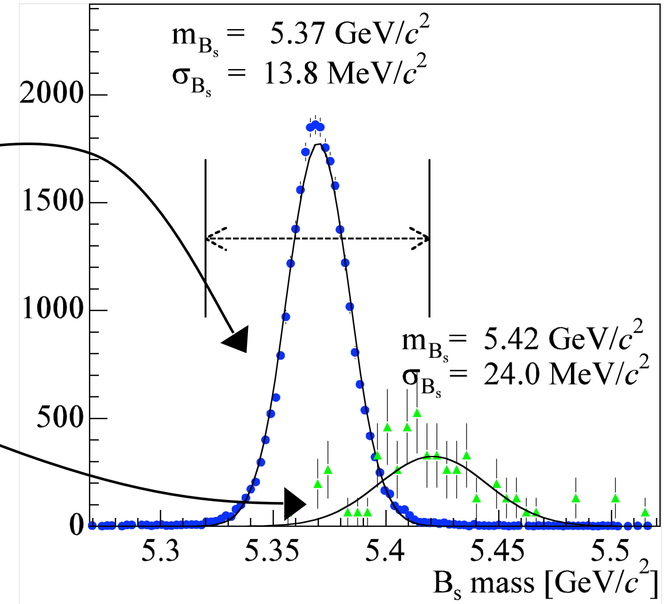
$\sigma(\sin(\phi_s)) = 0.058$

1. Angle γ from $B_s \to D_s K$

(2 Tree diagrams due to Bs mixing)

Simultaneous fit of $B_s \text{->} D_s \pi$ and $B_s \text{->} D_s K$:

- Determination of mistag fraction
- Time dependence of background



Time dependent asymmetries:

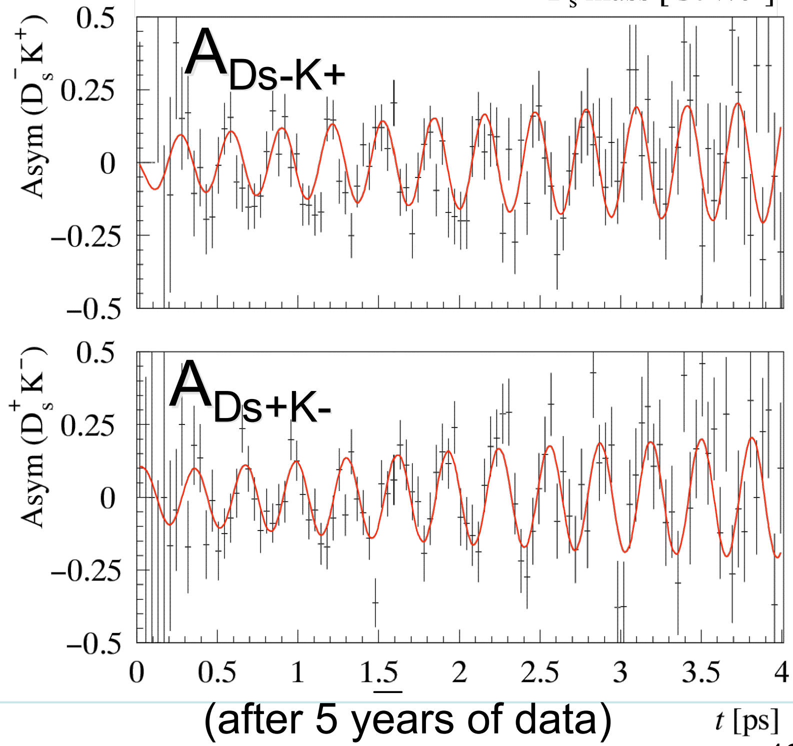
$B_s(\overline{B}_s) \text{->} D_s^- K^+$: _ $\Delta_{T1/T2} + (\gamma + \phi_s)$

$B_s(\overline{B}_s) \text{->} D_s^+ K^-$: _ $\Delta_{T1/T2} - (\gamma + \phi_s)$

After one year, if Δm_s = 20 ps^{-1}, $\Delta\Gamma_s/\Gamma_s$ = 0.1, 55 < γ < 105 deg, $-$20 < $\Delta_{T1/T2}$ < 20 deg:

$\sigma(\gamma)$ = 14–15 deg

No theoretical uncertainty; insensitive to new physics in B mixing



(after 5 years of data)

2. Angle γ from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$

(b->u processes, with large b->d(s) penguin contributions)

- Measure time-dependent CP asymmetries in $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays:

$$A_{CP}(t) = A_{dir}\cos(\Delta m\, t) + A_{mix}\sin(\Delta m\, t)$$

- Method proposed by R. Fleischer:
  - SM predictions:

$$A_{dir}(B^0 \to \pi^+\pi^-) = f_1(d, \theta, \gamma)$$
$$A_{mix}(B^0 \to \pi^+\pi^-) = f_2(d, \theta, \gamma, \phi_d)$$
$$A_{dir}(B_s \to K^+K^-) = f_3(d', \theta', \gamma)$$
$$A_{mix}(B_s \to K^+K^-) = f_4(d', \theta', \gamma, \phi_s)$$

$d\,\exp(i\theta)$ = function of tree and penguin amplitudes in $B^0 \to \pi^+\pi^-$

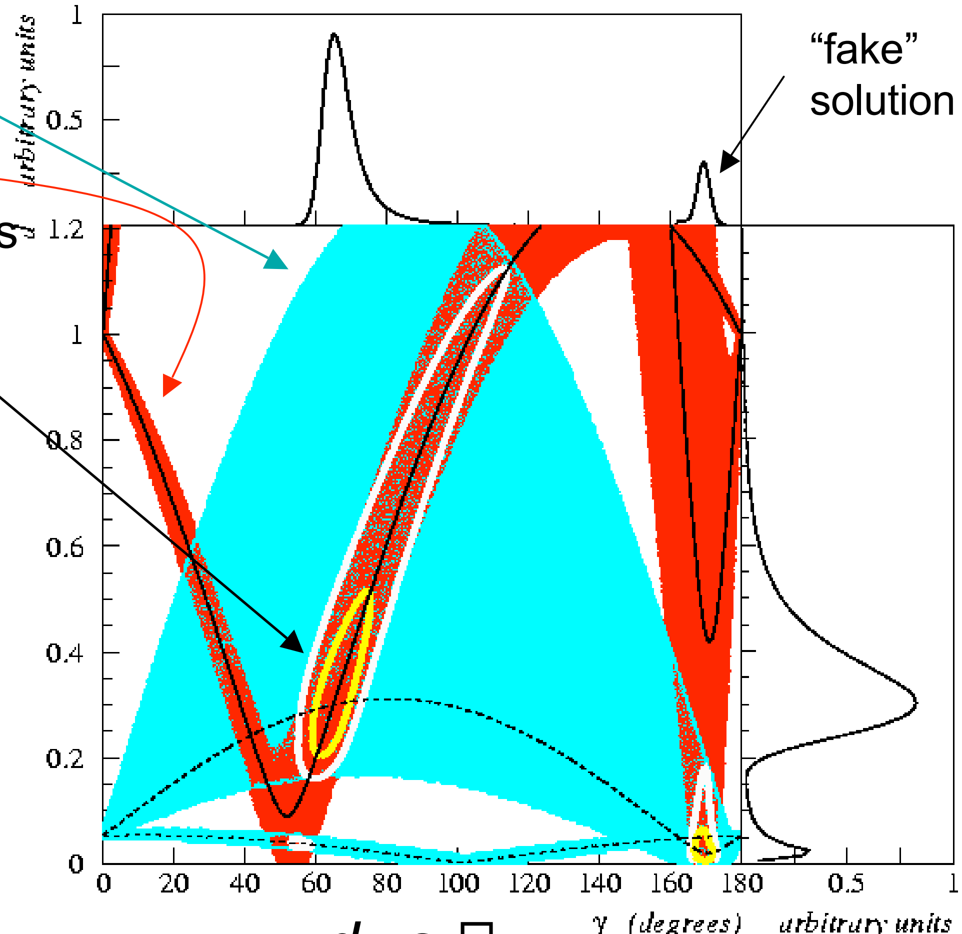
$d'\,\exp(i\theta')$ = function of tree and penguin amplitudes in $B_s \to K^+K^-$

  - Assuming U-spin flavour symmetry (interchange of d and s quarks): $d = d'$ and $\theta = \theta'$
  - 4 measurements (CP asymmetries) and 3 unknown (γ, d and θ) $\to$ can solve for γ

2. Angle γ from $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ (cont.)

- Extract mistags from $B^0 \to K^+\pi^-$ and $B_s \to \pi^+K^-$
- Use expected LHCb precision on ϕ_d and ϕ_s

blue bands from $B_s \to K^+K^-$ (95%CL)
red bands from $B^0 \to \pi^+\pi^-$ (95%CL)
ellipses are 68% and 95% CL regions
(for γ_{input} = 65 deg)



d vs γ

If Δm_s= 20 ps^{-1}, $\Delta\Gamma_s/\Gamma_s$=0.1,
d =0.3, θ= 160 deg,
55 < γ < 105 deg:

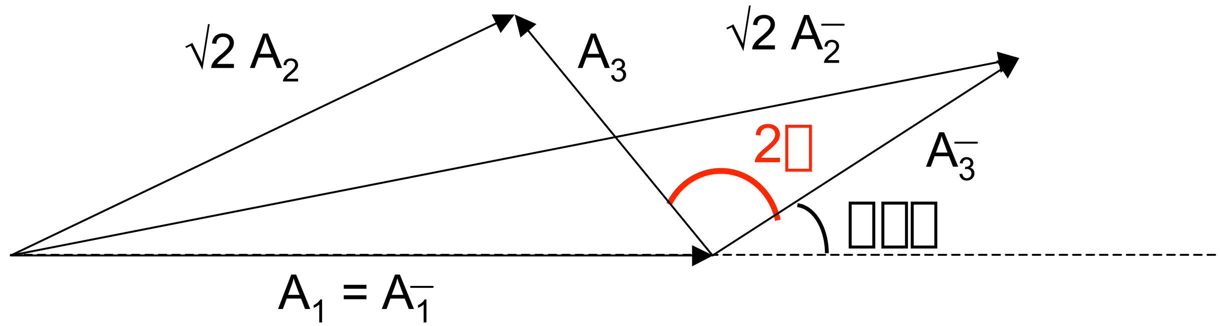
$\sigma(\gamma)$ = 4−6 deg

U-spin symmetry assumed; sensitive to new physics in penguins

3. Angle γ from $B^0 \to \bar{D}^0 K^{*0}$ and $B^0 \to D^0 K^{*0}$

(Interference between 2 tree diagrams due to D0 mixing)

- Application of Gronau-Wyler method to D^0K^{*0} (Dunietz):



- Measure six rates (following three + CP-conjugates):
  - 1) $B^0 \to \bar{D}^0(K^+\pi^-)K^{*0}$, 2) $B^0 \to D_{CP}(K^+K^-)K^{*0}$, 3) $B^0 \to D^0\,(K^-\pi^+)\,K^{*0}$
  - No proper time measurement or tagging required
  - Rates = 3.4k, 0.6k, 0.5k respectively (CP-conj. included), with B/S = 0.3, 1.4, 1.8, for γ=65 degrees and δ=0

$\sigma(\gamma)$ = 7–8 deg

55 < γ < 105 deg
−20 < δ < 20 deg

No theoretical uncertainty;
sensitive to new physics in D mixing

Measurement of angle □: New Physics?

1. Bs->DsK

□not affected by new physics in loop diagrams

2. B->□□, Bs->KK

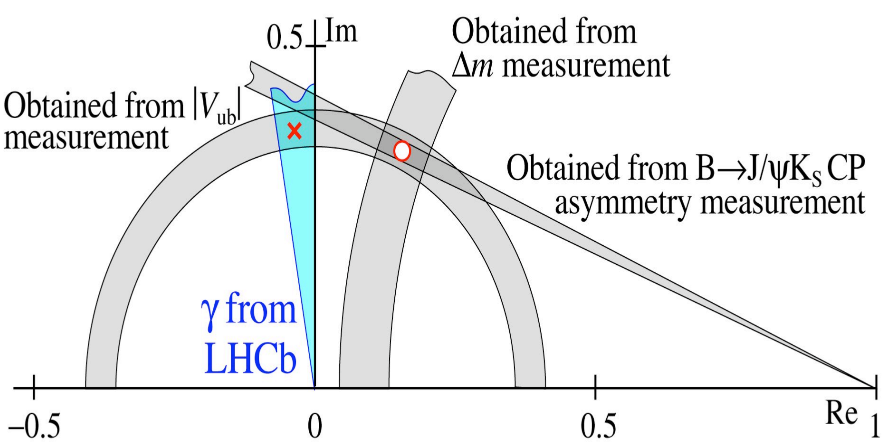
□affected by possible new physics in penguin

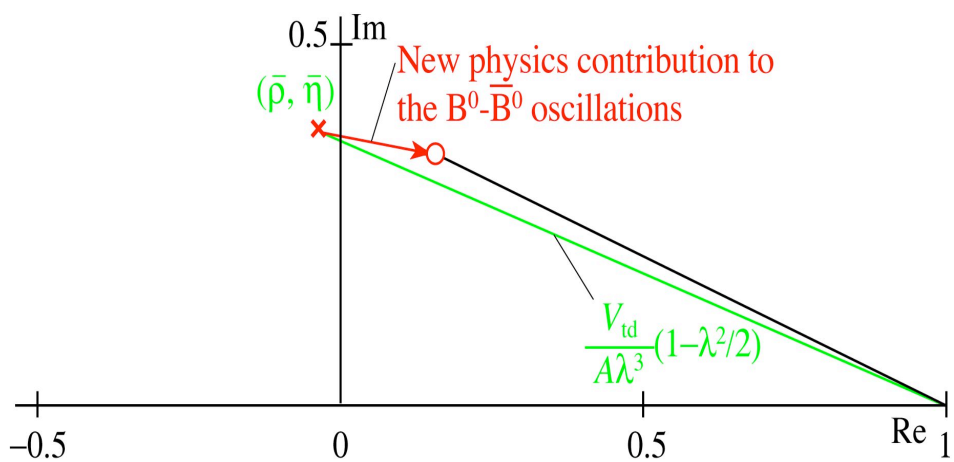
3. B->DK*

□affected by possible new physics in D-D mixing

- Determine the CKM parameters A,□,□ independent of new physics

- Extract the contribution of new physics to the oscillations and penguins





Systematic Effects

<u>Possible sources of systematic uncertainty in CP measurement</u>:

- Asymmetry in b-$\bar{b}$ production rate
- Charge dependent detector efficiencies…
  - can bias tagging efficiencies
  - can fake CP asymmetries
- CP asymmetries in background process

<u>Experimental handles</u>:

- Use of control samples:
  - Calibrate b-$\bar{b}$ production rate
  - Determine tagging dilution from the data:

    e.g. B_s->$D_s\pi$ for B_s->D_sK, B->Kπ for B->$\pi\pi$, B->J/ψK* for B->J/ψK_s, etc
- Reversible B field in alternate runs
- Charge dependent efficiencies cancel in most B/$\bar{B}$ asymmetries
- Study CP asymmetry of backgrounds in B mass “sidebands”
- Perform simultaneous fits for specific background signals:

  e.g. B_s->$D_s\pi$ in B_s->D_sK , B_s->Kπ & B_s->KK, …

Conclusions

- LHC offers great potential for B physics from “day 1” LHC luminosity
- LHCb experiment has been reoptimized:
  - Less material in tracking volume
  - Improved Level1 trigger
- Realistic trigger simulation and full pattern recognition in place
- Promising potential for studying new physics